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Optimal integral force feedback for active vibration control

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ABSTRACT

This paper proposes an improvement to Integral Force Feedback (IFF), which is a popular method for active vibration control of structures and mechanical systems. Benefits of IFF include robustness, guaranteed stability and simplicity. However, the maximum damping performance is dependent on the stiffness of the system; hence, some systems cannot be adequately controlled. In this paper, an improvement to the classical force feedback control scheme is proposed. The improved method achieves arbitrary damping for any mechanical system by introducing a feed-through term. The proposed improvement is experimentally demonstrated by actively damping an objective lens assembly for a high-speed confocal microscope.

1. Introduction

The presence of undesirable vibrations is known to degrade the performance of structural and mechanical systems that may lead to system failures and malfunctions [1]. Vibrations appear due to the unwanted excitation of system resonances. A common method for reducing vibration is to artificially increase the viscous damping in the system. Damping control can be classified into passive or active. Examples of traditional passive approaches include viscoelastic damping and tuned-mass absorbers [2]. These approaches are commonly integrated into the structural or mechanical design and eliminate the need of additional controlled hardware and sensors. However, passive damping methods can be sensitive to changes in resonance frequencies, may be bulky, and may not perform well at low frequencies. On the other hand, active damping control has the potential to overcome the performance limitations of passive damping methods [3,4]. Active control typically requires the integration of sensors and a feedback control system to artificially increase the damping ratio of a system.

Active damping control can be found in scientific and industrial applications where the speed and accuracy are key performance criteria, for example, scanning probe microscopy [5–8], nano-fabrication [9,10], precision optics [11,12], robotics [13], medical [14] and aerospace systems [15]. In addition, active damping control can also be found in defence applications where the system lifetime is important [16]. A number of techniques for damping control have been demonstrated successfully in the literature, these include Positive Position Feedback (PPF) [17], polynomial based control [18], acceleration feedback [19], shunt control [20,21], resonant control [22], Force Feedback [23–26], and Integral Resonance Control (IRC) [27,28]. Among these techniques, PPF controllers, velocity feedback controllers, force feedback controllers, and IRC controllers have been shown to guarantee stability when the plant is strictly negative imaginary [29]. Controllers with automatic synthesis have also been successfully applied to vibration control applications. Examples include robust

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$\mathcal{H}_\infty$ controllers [30–32] and LMI based controllers [33]. However, such methods are rarely used in practice because of their implementation complexity.

In Refs. [23–26] Integral Force Feedback (IFF) is described for vibration control. This technique utilizes a force sensor and an integral controller to directly augment the damping of a mechanical system. The major advantages of IFF are the simplicity of the controller, guaranteed stability, excellent performance and robustness to variation of resonance frequency. However, the maximum damping achievable with IFF is a function of the system properties, in particular the system's stiffness relative to the actuator stiffness. This means that some systems can be critically damped using IFF while other systems exhibit insufficient damping.

In this work, an improvement to integral force feedback is described which allows an arbitrary damping ratio to be achieved for a mechanical system. The modification amounts to replacing the integral controller with a first-order low-pass filter. Although the additional complexity is negligible, the damping performance is significantly improved. This result allows integral force feedback control to be applied to systems that were not previously suited.

2. Classical integral force feedback (CIFF)

Integral force feedback control has been widely employed for augmenting the damping of flexible structures. The feedback law is simple to implement and under common circumstances provides excellent damping performance with guaranteed stability. Fig. 1 illustrates a structure G equipped with a piezoelectric actuator that produces a force F_a with internal stiffness K_a. A force sensor is collocated with the piezoelectric actuator and measures the axial force F_s acting on the system G. The variable d represents the mechanical displacement.

The classical integral force feedback controller has a block diagram representation illustrated in Fig. 2. The transfer function between the unconstrained piezo expansion δ to the sensor force F_s is adapted from [23]

$$G_{F_s\delta}(s) = \frac{F_s}{\delta} = K_a\left\{1 - \sum_{i=1}^{n} \frac{\nu_i}{1+s^2/\omega_i^2}\right\}, \tag{1}$$

where ω_i is the natural frequency of the system and ν_i is the fraction of modal strain energy for the ith mode. The modal zeros z_i are given as

$$z_i^2 = \omega_i^2(1-\nu_i). \tag{2}$$

The integral force feedback controller is

$$C_{d1}(s) = \frac{K_{d1}}{K_a s}, \tag{3}$$

where K_{d1} is the gain of controller. The maximum modal damping is [23]

$$\zeta_i^{\max} = \frac{\omega_i - z_i}{2\omega_i}, \tag{4}$$

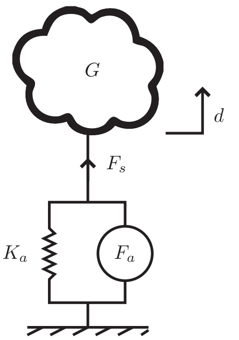

Fig. 1. Structure G with a piezoelectric transducer.

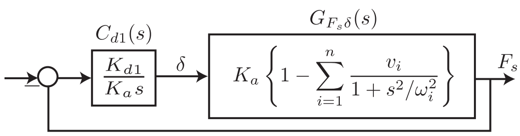

Fig. 2. Block diagram representation of Classical Integral Force Feedback.